Year: 2020

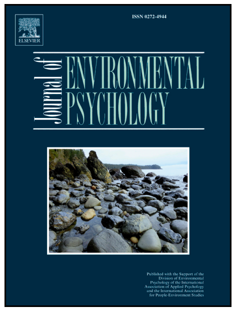
The advantage of globally visible landmarks for spatial learning

Credé, Sascha ; Thrash, Tyler ; Hölscher, Christoph ; Fabrikant, Sara I

Abstract: Despite much recent interest, it is unclear which types of landmarks are best suited for survey knowledge acquisition. Thus, we investigated the accuracy of survey knowledge after the learning of sequentially visible (local) landmarks and simultaneously visible (global) landmarks from a first-person perspective during navigation through a virtual city. We also assessed systematically the role of working memory during navigation with a concurrent spatial-sequential task. Our results indicate that the learning of local and global landmark configurations are similarly affected by this concurrent task. We also find greater accuracy for the acquisition of global landmark knowledge compared to local landmark knowledge, especially for participants with high working memory capacity.

DOI: https://doi.org/10.1016/j.jenvp.2019.101369

Originally published at:
Credé, Sascha; Thrash, Tyler; Hölscher, Christoph; Fabrikant, Sara I (2020). The advantage of globally visible landmarks for spatial learning. Journal of Environmental Psychology, 67:101369.
DOI: https://doi.org/10.1016/j.jenvp.2019.101369



The advantage of globally visible landmarks for spatial learning

Sascha Credé, Tyler Thrash, Christoph Hölscher, Sara Irina Fabrikant

PII: S0272-4944(19)30280-4

DOI: https://doi.org/10.1016/j.jenvp.2019.101369

Reference: YJEVP 101369

To appear in: *Journal of Environmental Psychology*

Received Date: 25 April 2019

Revised Date: 15 October 2019

Accepted Date: 1 November 2019

The advantage of globally visible landmarks for spatial learning

Sascha Credé[1], Tyler Thrash[1,2,3], Christoph Hölscher[2] & Sara Irina Fabrikant[1,3]

[1]University of Zurich, Department of Geography, Geographic Information Visualization and Analysis, Winterthurerstrasse 190, 8057 Zurich, Switzerland

[2]ETH Zurich, Department of Humanities, Social and Political Science, Chair of Cognitive Science, Clausiusstrasse 59, 8092 Zurich, Switzerland

[3]University of Zurich, Digital Society Initiative, Rämistrasse 66, 8001 Zurich, Switzerland

Author Note

This research was funded by Swiss National Science Foundation (SNF number: 156072). The authors thank Lars Konieczny for his very helpful advice concerning the data analysis and Raphael Weibel and Joonas Karjalainen for automating parts of the EDA analysis procedure.

Abstract

Despite much recent interest, it is unclear which types of landmarks are best suited for survey knowledge acquisition. Thus, we investigated the accuracy of survey knowledge after the learning of sequentially visible (local) landmarks and simultaneously visible (global) landmarks from a first-person perspective during navigation through a virtual city. We also assessed systematically the role of working memory during navigation with a concurrent spatial-sequential task. Our results indicate that the learning of local and global landmark configurations are similarly affected by this concurrent task. We also find greater accuracy for the acquisition of global landmark knowledge compared to local landmark knowledge, especially for participants with high working memory capacity.

Keywords: working memory, spatial knowledge acquisition, navigation, landmarks, virtual reality, individual differences

The advantage of globally visible landmarks for spatial learning

Introduction

Imagine a tourist visiting a city for the first time. While she is exploring the unfamiliar urban environment on foot with her traveling companions, she is also taking pictures of sights, looking for dining options on a smart device, and chatting with her companions. In this demanding context, to which types of landmarks should she attend to gain an understanding of the city's layout? Prior research has suggested that landmarks support spatial knowledge acquisition by structuring the vast amount of available environmental information into mental spatial representations at higher levels of abstraction (Couclelis, Golledge, Gale, & Tobler, 1987; Golledge, 1999; Sadalla, Burroughs, & Staplin, 1980). For example, our tourist might remember a visually salient statue that can serve her as a mental anchor and support the encoding and recall of other locations in its surroundings (Sadalla et al., 1980). Memory concerning the relative directions and distances to various location anchors within a spatial reference system will eventually provide her with survey knowledge of the traversed environment (O'Keefe, 1991; Siegel & White, 1975). Indeed, global landmarks, visible from many locations in an environment or on a map, seem to be particularly helpful for orientation and acquiring survey knowledge because they provide a visually accessible spatial reference frame (H. Li, Corey, Giudice, & Giudice, 2016; Steck & Mallot, 2000). The display of global landmarks on digital navigation assistants can support in situ orientation and the recall of survey knowledge (R. Li, Korda, Radtke, & Schwering, 2014; Schwering, Krukar, Li, Anacta, & Fuest, 2017).

However, the roles that local and global landmarks play in survey knowledge acquisition have not been clarified conclusively (Castelli, Latini Corazzini, & Geminiani, 2008; Credé, Thrash, Hölscher, & Fabrikant, 2019). In particular, no studies have examined the effects of learning global, as compared to local, landmark configurations with respect to high concurrent task demands that might reduce a navigator's ability to encode spatial relations in working memory.

In a previous virtual reality study, we found no significant improvement in survey knowledge for global landmark configurations as compared to local landmark configurations in situations with and without time pressure (Credé et al., 2019). One possible explanation for this result is that the global landmarks were placed at a great viewing distance while local landmarks were placed along the route. Participants could not take advantage of path integration to acquire global landmark knowledge, and the path integration advantage for learning local landmark configurations may have offset any global visibility advantages for learning global landmark configurations.

Thus, we aimed to assess further the quality of survey knowledge acquisition for local and global landmarks when they are both located along the route. To better understand a navigator's ability to encode local and global landmark configurations in working memory (WM), we included a concurrent spatial task in the study. Concurrent spatial tasks interfere selectively with the active processing of spatial information in WM and were used in this study to reveal the learning utility of both landmark types when learners operate on limited cognitive resources, for example, when carrying out multiple tasks during navigation. We expected an increase in cognitive load and for this increase to manifest in increased psychophysiological arousal (Engström, Johansson, & Östlund, 2005), increased self-reported distress (Matthews et al., 1999), and impaired survey knowledge acquisition (Wen, Ishikawa, & Sato, 2013).

The role of working memory in survey knowledge acquisition

WM is crucial for survey knowledge acquisition during navigation through environmental spaces because it provides the cognitive resources needed to store information bits temporarily during travel and combine them into a common memory structure (G. L. Allen, Kirasic, Dobson, Long, & Beck, 1996; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). However, WM capacity is limited and thus the concurrent execution of tasks results in decreased performance in at least one of these tasks. Impaired performance in such a dual task condition indicates that the same set of WM resources are involved in both tasks (Lindberg & Gärling, 1981).

WM consists of one domain-general (i.e., episodic buffer) and two domain-specific storage systems. The domain-specific phonological loop and visuospatial sketchpad are used to temporarily store verbal and visuospatial information, respectively. An attentional control system (i.e., the central executive) allows one to attend to information from the two storage systems and combine it with information from long term memory (Baddeley, 2000). According to the WM model developed by Baddeley 2000, interference between storing and processing information occurs only when the processing task generates mental representations that occupy the same capacity-limited and domain-specific storage system as the memory task (Baddeley, 2000; Oberauer & Göthe, 2006). The visuospatial storage system seems to be further separated into a visual and spatial component, which are largely independent of one another (e.g., Darling, Della Sala, & Logie, 2007; Logie & Marchetti, 1991).

Navigation research indicates that the involvement of WM subsystems changes with particular tasks (e.g., Coluccia, Bosco, & Brandimonte, 2007; Gras, Gyselinck, Perrussel, Orriols, & Piolino, 2013; Labate, Pazzaglia, & Hegarty, 2014; Wen et al., 2013). These dual-task studies showed that the involvement of spatial WM in survey knowledge acquisition is comparatively low if object-to-object relations can be assessed simultaneously from a single viewpoint, for example when learning landmarks from a map (Coluccia et al., 2007). The involvement of spatial WM is comparatively high if object-to-object relations need to be integrated sequentially, as when landmarks are only visible locally and navigators perceive one at a time (Gras et al., 2013; Labate et al., 2014; Wen et al., 2013). Even though it seems that distinct encoding mechanisms in WM are involved when information is presented sequentially or simultaneously during navigation, these studies did not investigate the spatial memory effect of the presentation modes directly.

Simultaneous and sequential viewing

A majority of prior studies involving desktop- and room-sized spaces report an improvement in spatial memory performance for configurations of objects that are presented simultaneously instead of sequentially (Blalock & Clegg, 2010; Lecerf & De Ribaupierre, 2005; Lupo et al., 2018). For example, Blalock and Clegg (2010) and Lecerf and de Ribaupierre (2005) found improved recognition performance in the simultaneous condition after participants learned multiple shapes presented on a computer screen.

There are at least two different explanations for a spatial memory advantage resulting from simultaneous presentation over sequential presentation, including flexibility in the order in which items can be attended (Lupo et al., 2018; Mackworth, 1962) and the relational organization of visuospatial WM (as opposed to item-focused organization, Blalock & Clegg, 2010; Jiang, Olson, & Chun, 2000). According to the flexibility explanation, the memory advantage provided by simultaneous viewing emerges from being able to scan multiple positions flexibly and in one's preferred order (Lupo et al., 2018; Mackworth, 1962). According to the relational organization explanation, humans remember spatial information as parts of configurations rather than as absolute locations in space (Blalock & Clegg, 2010; Jiang et al., 2000; Lecerf & De Ribaupierre, 2005). While empirical evidence appears to favor simultaneous presentation for accurate object-to-object memory (but see Yamamoto & Shelton, 2009) these studies used a stationary observer and objects in figural space (R. J. Allen, Baddeley, & Hitch, 2006; Blalock & Clegg, 2010; Lecerf & De Ribaupierre, 2005) or an observer that could move very short distances in vista space (Lupo et al., 2018). Because cognitive processes change with spatial scale (Montello, 1993; Sholl & Fraone, 2004), it is unclear if the benefits of simultaneous presentation over sequential presentation hold for larger spaces such as a city.

Two studies by Meilinger, Strickrodt, and Bülthoff (2016) and Ruotolo, Ruggiero, Vinciguerra, and Iachini (2012) compared memory for object-to-object relations after sequential or simultaneous learning in environmental spaces. Importantly, these studies were conducted in room-sized environmental spaces in which sequential processing was operationalized by obstructing visibility with walls. In accordance with research using figural spaces, Meilinger et al. (2016) found that simultaneous learning resulted in higher accuracy in object-to-object memory than sequential learning requiring movement. Similarly, Ruotolo et al. (2012) found that metric distortions in spatial memory were more pronounced when information was learned sequentially and that these distortions accumulated as the spaces increased in size. For the present study, we therefore examine the learning of spatial locations during navigation through a city, where WM resources should be more involved in integrating these locations in a piecemeal manner over time (Fisk & Sharp, 2003; Hegarty et al., 2006).

Individual differences in the cognitive abilities of navigators also explain performance differences on spatial knowledge acquisition tasks (Ishikawa & Montello, 2006; Wolbers & Hegarty, 2010). WM span tasks have been used to differentiate individuals' abilities to maintain information actively in memory under the simultaneous processing demands of other tasks (Münzer, Zimmer, & Baus, 2012; Oberauer, Lange, & Engle, 2004). The concept of WM span aligns with Baddeley's (2000) WM model of a limited-capacity system for simultaneous storage and processing. Specifically, WM span predicts performance under high cognitive load (e.g., navigating under concurrent task demands) because individuals with low WM spans are worse at maintaining and updating relevant information in memory (Ilkowska & Engle, 2010).

The present study

Our study investigated the role of WM in acquiring survey knowledge of sequentially (locally) or simultaneously (globally) visible landmark configurations during navigation through virtual cities. Participants were asked to follow a route and learn the locations of highlighted landmarks. We then assessed participants' survey knowledge using judgments of relative direction (JRD) for these landmark configurations. We expected higher accuracy of JRDs for global than for local landmark configurations. Furthermore, we compared participants' learning performance in each landmark condition either with or without a concurrent spatial-sequential task. Relying on the interference paradigm, we expected that this additional task would impair survey knowledge acquisition for local and global landmark configurations to the extent that spatial WM was involved in the task. Specifically, we hypothesized that increased spatial WM demands impair survey knowledge more for sequentially visible local landmarks than for simultaneously visible global landmarks. We also assessed individuals' WM spans because we expected high WM spans to be beneficial in the sequential integration of local landmarks over time and to shield the individuals from the detrimental effects of the concurrent task on survey knowledge acquisition. Ultimately, the study aimed to better understand the conditions (i.e, with or without spatial concurrent task, WM span) in which navigators can form survey representations of different aspects of the same environment (i.e., local or global landmarks).

Method

Participants

The study was conducted in German. Participants were recruited via the psychology recruitment server from the University of Zurich (https://www.psychologie.uzh.ch/probandenserver/). Fifty-four people participated in the study for monetary compensation. The sample size of fifty-four participants with twenty-seven in each between-subjects condition was determined before data collection. Two participants did not complete the study due to slight nausea. Fifty-two participants between the ages of 18 and 36 (M=25.6 years, SD=4.5, 26 women) completed all of the experimental tasks.

Ethics statement

All of the procedures performed in this study were performed in accordance with the ethical standards of the Swiss Psychological Society and the American Psychological Association.

Materials

Apparatus. We employed a three-wall virtual reality (VR) system called the CAVE that simulates stereoscopic vision using frame sequential projection (1280 pixel x 800 pixel resolution at 120Hz frequency). Some of the devices and methods we used in the present study have already been described in detail (Credé et al., 2019) . Figure 1 shows a photograph of a participant in the CAVE during the experiment. A 70 cm tall cabinet was placed next to the participant (on the side of the dominant hand) and functioned as an armrest and table for the numeric keypad. Participants navigated through virtual cities at 3.8 m/sec using a foot-operated control interface (3D Rudder, Aix-en-Provence, FR; https://www.3drudder.com). Forward or backward movement required participants to tilt the interface with their feet towards the front or back, respectively. Tilting the interface to the right or left resulted in rotating the view to the right or left, respectively. The experimental tasks were rendered with Vizard 5.6 (WorldViz, CA, USA; https://www.worldviz.com). The city models were designed using City Engine 2014 (Esri, CA, USA; http://www.esri.com/software/cityengine). Electrodermal activity (EDA) was recorded using AcqKnowledge 4.4 (Biopac Systems, CA, USA) and analyzed using LedaLab, a Matlab-based software for analyzing skin conductance data (Benedek & Kaernbach, 2010). EDA recordings from AcqKnowledge were synchronized in real-time with the experimental procedure from Vizard.

Virtual Environments. The two city models used for navigation each had an area of approximately 0.4 km^2 that was covered with buildings, trees, streets, and open spaces. Except for four high-rise buildings (80 m to 100 m tall), the cities contained low-rise

Figure 1. Photograph of the experimental setup with the participant sitting on a chair 30 cm back from the center of the VR system (CAVE).

buildings with heights between 5 m and 15 m. The sidewalk widths of all streets were 5 m, and the widths of the streets that were part of the navigated routes were all 7 m. Approximately one-fifth of each city block was covered with open space instead of buildings. The cities were flat without any slopes, hills, or mountains. Figure 2 depicts a top-down view of the street network and the routes in each city.

For each city, we selected a set of four low-rise buildings and four high-rise buildings located along the route. Depending on the landmark condition, either the set of low-rise buildings or the set of high-rise buildings was highlighted, although both sets of landmarks were visible in both conditions (see Figure 3). Participants' learning task during navigation was to memorize the relative locations of these highlighted buildings (i.e., target landmarks). Due to the surrounding buildings, low-rise target landmarks were strongly restricted in visibility (i.e., local landmarks), and participants could only perceive one at a time (i.e., sequential viewing). In contrast, high-rise target landmarks were relatively tall and visible from multiple proximate and distant locations along the route (i.e., global landmarks), and participants could view more than one at a time (i.e., simultaneous viewing). Figure 3 depicts one of the virtual cities from the same viewpoint but in different landmark conditions. Notably, because we did not remove any buildings from the environment in any condition, participants could have acquired survey knowledge from both target and non-target landmarks. However, we only evaluated survey knowledge for the highlighted target landmarks.

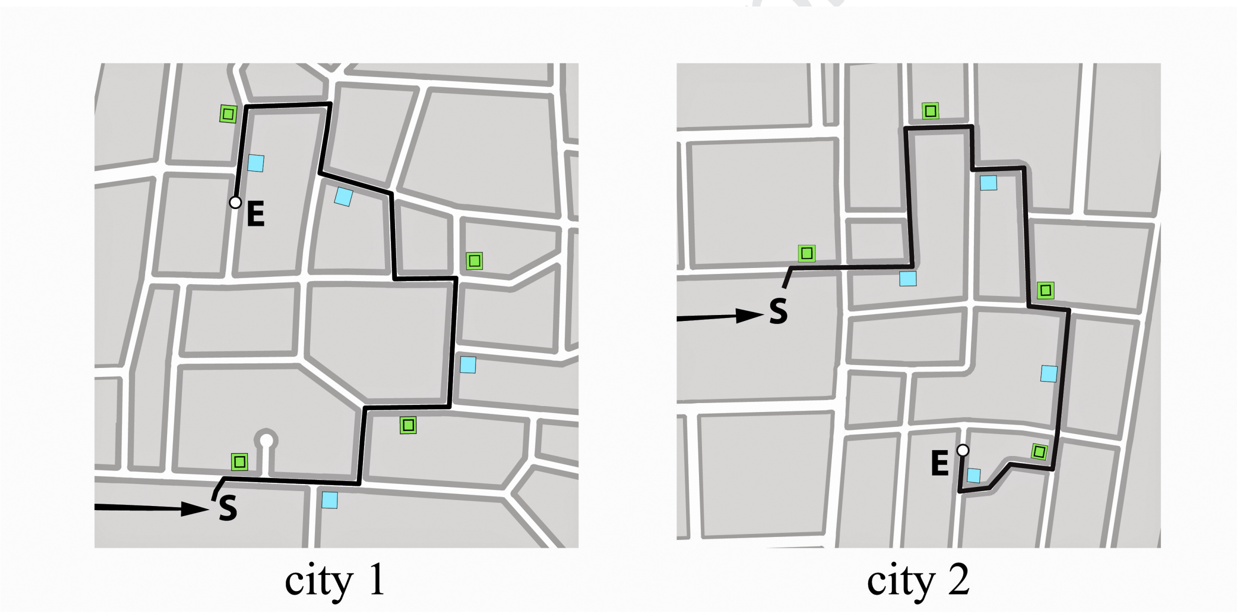
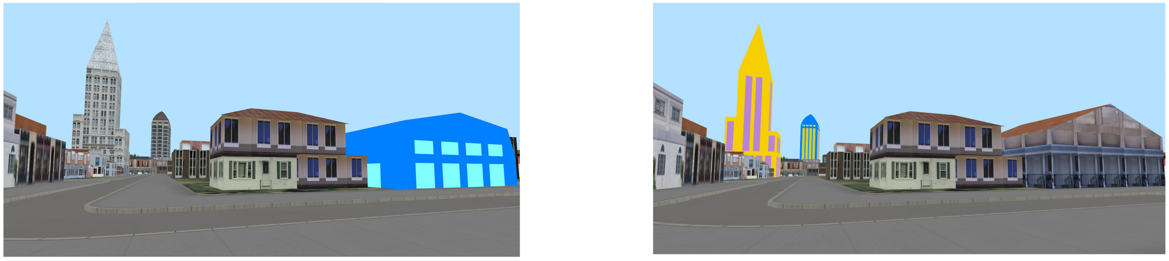


Figure 2. Each route was approximately 950 m long. Double squares (green) represent the landmark locations in the global condition, and single squares (blue) represent the landmark locations in the local condition.

During the navigation task, participants could display a visual routing assistant in the center of the front screen of the CAVE, including a map of the city with a footprint of 0.026 km^2 and a 1:156 map scale. The map depicted the location of the user at its center and was oriented with respect to the user's heading direction. The map contained the street network and the highlighted route towards the destination but did not depict



(a) (b)

Figure 3. Screenshots of one of the virtual cities in each of the two landmark conditions taken from the same viewpoint. Participants' learning task during navigation was to specifically memorize the relative locations of highlighted buildings. (a) In the local landmark condition, a set of four local landmarks were highlighted. (b) In the global landmark condition, a set of four global landmarks were highlighted. The same buildings were present in both conditions, but only the target buildings were highlighted in the virtual environment and tested with the JRD task.

buildings or landmarks. While the map was displayed, the side screens turned black and movement through the virtual environment was disabled until three seconds after using the map. The design of this navigational aid was inspired by contemporary designs and aimed to facilitate route-following while hindering survey learning directly from the map itself.

JRDs. To assess participants' memory for relative spatial relations (see Shelton & McNamara, 2004), we employed a CAVE version of the JRD task (Credé et al., 2019). In this task, the previously traveled environment was not visible. Participants stood in the center of the CAVE facing a crosshair displayed on the front screen. Participants were asked to imagine standing at a first landmark while facing a second landmark (i.e., located in the direction of the crosshair) and to point to a third landmark. For each JRD, participants held an electronic pointing device in the estimated direction of the third landmark and confirmed their decision by pressing a button. The orientation of the device was tracked by an inertial measurement unit and four optical sensors surrounding the CAVE. For these JRDs, we used only the highlighted target landmarks of the previously traversed environment. Hence, participants judged directions either exclusively among local or exclusively among global landmarks. In each city with 4 target landmarks, there were 24 permutations of JRD trials which can be grouped into 12 symmetrical pairs (e.g., permutation ABC and ACB would have -40 and 40 degree JRD error, respectively). To provide each participant with 12 unsymmetrical trials, a script randomly excluded one permutation from each of the 12 symmetrical pairs.

Spatial tapping task. A spatial tapping task introduced additional processing demands concurrent to navigation and learning the landmark configurations. The spatial tapping task involved the continuous typing of a predefined series of six numbers (7–6–1–3–4–9) at a rate of one keystroke per second on a 3x3 matrix numeric pad. To improve blind tapping, we removed keys that were not part of the tapping task. The tapping sequence was inspired by the pattern used by Labate et al. (2014).

Test and questionnaires. To assess participants' WM spans, the Symmetry Span Test (Kane et al., 2004) presented locations one at a time as filled grid cells in a 5x5 matrix. Each participant's primary task was to recall a sequence of locations after the presentation phase was finished. Between the presentations of different locations, a processing task required participants to judge the symmetry of a pattern displayed in an 8x8 matrix. For each of 13 trials, the memory sequences ranged from 2 to 6 cells. We also administered two questionnaires. In the Simulator Sickness Questionnaire (SSQ) Kennedy, Lane, Berbaum, and Lilienthal (1993), participants rated 16 symptoms on a 4-point scale from absent to severe. These ratings were used to generate scores for three subscales (i.e., nausea, disorientation, and oculomotor symptoms) and a total score. In the Short Stress State Questionnaire (SSSQ), participants responded to questions that indicated their feelings of distress, engagement, and worry (Helton, 2004). Both questionnaires were administered once before (pre-task) and once after (post-task) the experiment.

Gamification. A scoring system was used to motivate participants. Participants' overall scores were visible at the top of the front screen throughout the experiment, and participants knew that their compensation (between 10 CHF and 20 CHF) would depend on their score. Specifically, we told participants that their overall scores changed with their performance on the navigation, tapping, and JRD tasks. Participants lost one point every 10 seconds during the navigation phase and could earn points via accurate performance on JRD trials. After finishing one set of JRD tasks, a pointing accuracy score was displayed and added to the overall score. This score was computed by subtracting the mean angular error of 12 JRD trials from 180. In order to avoid strategic trade-offs, participants were instructed that a "good" overall score could only be achieved when all tasks were performed well. However, participants were not told the exact manner in which their overall scores were computed. Only during tapping was a 1-point penalty subtracted from a participant's score during navigation if their mean tapping rate exceeded one hit per second for longer than three seconds. Furthermore, hitting an incorrect key resulted in a penalty of 0.5 seconds added to the mean tapping rate. A beeping sound and a symbol appearing on the top of the front screen signaled every time the system subtracted a point due to insufficient or incorrect tapping activity.

Procedure. Participants were tested individually. After participants received a standardized overview of the experimental tasks, they provided informed consent. Then the participants completed the pre-task tests and questionnaires (i.e., SSQ, SSSQ, Symmetry Span Test) on a desktop computer. Subsequently, the experimenter cleaned the skin at the medial phalanges of participants' index and middle fingers with a light abrasive gel and attached solid gel electrodes at these locations (Figner & Murphy, 2011). After electrode functionality was verified, participants rested for two minutes to ensure the hydration of the skin by the gel. Next, participants watched a 150-second nature video projected on the front screen of the CAVE. EDA recordings during this video were used as a baseline to account for individual differences in physiological reactivity to acute stress states or external workload (Ulrich, 1981). Next, the participants read the instructions for the upcoming tasks. In the CAVE, participants first practiced with the controls by collecting items in a virtual environment using the 3D rudder. After completing this task successfully, the participants were led through all components of each experimental trial (e.g., navigation, map use, and the JRD task) by the experimenter. We designed an extra city for this training trial. Once the participants in the group without tapping had no further questions, the experimenter started the main experiment. Participants in the tapping group received the same introduction except that the experimenter introduced the tapping procedure during a predefined interval in the training task. Participants finished the last 50 m of the navigation task while performing the tapping task concurrently. Then we recorded baseline measurements of performance on the tapping task. Participants were instructed to tap as accurately and quickly as possible for 30 seconds. After this baseline measurement, and if a participant had no further questions, the experimenter started the main experiment.

The main experiment consisted of two blocks. Each experimental block consisted of a train ride, a navigation task, and a series of JRDs. The 30-second train ride served to increase the believability of the navigation task (Freeman, Lessiter, Pugh, & Keogh, 2005). After the train ride, the participant's viewpoint was moved out of the virtual train automatically to begin the navigation task through the city. During the navigation phase, participants were asked to follow the route indicated on the navigational aid as quickly as possible and to memorize the relative locations of the highlighted landmarks as accurately as possible. The number of highlighted landmarks was initially unknown to the participants. Participants were instructed explicitly not to prioritize one of the given tasks (i.e., following the route, memorizing the landmarks, or tapping). Participants were also asked not to stray from the route marked on the navigational aid. When a participant left the route, a message appeared asking them to return to the marked route. Participants finished the navigation task when they arrived at the destination. After each navigation trial, participants' survey knowledge was assessed using 12 JRDs. Participants were asked to point as accurately as possible and were instructed that there was no time limit for their decisions. Pointing accuracy was recorded automatically by the system. After the main experiment, participants completed the post-task SSQ and SSSQ questionnaires.

Design & analysis

This experiment included two categorical independent variables in a 2 (with / without tapping task) x 2 (local / global landmarks) mixed factorial design. Participants were randomly assigned to either the with or without tapping group (i.e., between-subjects), but all participants completed both landmark conditions (within-subjects in a counterbalanced order). WM span was also included as an observed continuous explanatory variable. Response variables included JRD error, the SSQ and SSSQ data, tapping data, and EDA.

JRDs. JRD error was defined as the absolute angular difference between the estimated direction and the actual direction of a target relative to the reference landmarks. These angular errors could vary between 0° (very accurate) and 180° (very inaccurate). The errors were analyzed with linear mixed effects models using the lmer function from the "lme4" package (version 1.1-18-1; Bates, Mächler, Bolker, & Walker, 2015) implemented in R version 3.5.2 (R Core Team, 2018). Models were fitted using restricted maximum likelihood estimations. P-values were derived using the R package "lmerTest" (Kuznetsova, Brockhoff, & Christensen, 2017) which applies Satterthwaite approximations of degrees of freedom. Post-hoc marginal effect estimations were computed using the R package "emmeans" (version 1.3.2; Lenth, 2019). We did not discard any outliers from the JRD analyses.

WM span. For our WM span measure, we did not consider processing performance (i.e., symmetry judgments). However, we excluded one participant from the analysis who performed below 85% accuracy in symmetry judgments (following Kane et al., 2004). To compute participants' WM storage performance, we used a partial-credit unit scoring (PCU) method. Empirical results favor partial-credit unit scoring because credit is given to fully and partially correct answers (e.g., Conway et al., 2005).

Questionnaires. For the SSQ, we applied the established weighting score procedure developed by Kennedy and colleagues (1993) to obtain a single score for each of the three subscales and a global index that reflected the overall discomfort level. We conducted four paired-sample t-tests (two-tailed) with a Bonferroni adjusted alpha level of .0125 (.05/4) per test. For the SSSQ, we computed scores by averaging across the eight items of each subscale (Helton, 2004). From these averages, we computed change scores by subtracting the pre- from the post-task score. For significant t-tests, we provided Cohen's d measure of effect size using the R package "lsr" (Navarro, 2015) with pooled standard deviations.

Tapping data. To examine mean differences in change scores between the with and without tapping groups, we conducted independent-samples t-tests (two-tailed) for each of the three subscales (distress, engagement, worry) with a Bonferroni adjusted alpha level of .01666 (.05/3) per test. For the tapping data, we computed the number of correct tapping responses per second (correct tapping rate) for each navigation trial and the baseline trial. We performed paired-sample (two-tailed) t-tests with a Bonferroni adjusted alpha level of .025 (.05/2) per test to understand whether participants' tapping performance during navigation changed significantly from their baseline measurement and whether that change was similar between landmark conditions.

EDA. We extracted the EDA signal at 1000 Hz and down-sampled to 10 Hz without applying any post-hoc filters. We excluded three participants from the analysis due to substantial movement artifacts in the signal. Then we conducted a continuous decomposition analysis to decompose the raw signal into continuous tonic and phasic activity (Benedek & Kaernbach, 2010). Arousal was operationalized as a positive change in the tonic component of EDA (i.e., skin conductance level or SCL) or as an increase in non-specific skin conductance responses per minute (nSCRs/min, Boucsein, 2012). To check the expected difference in arousal between the with and without tapping groups, we submitted the mean EDA increases from baseline to independent-samples t-tests (two-tailed) with a Bonferroni adjusted alpha level of .025 (.05/2) per test.

Structure of statistical model. To identify the maximal appropriate random effects structure that would converge, we devised a model that included JRD errors as a response variable, no fixed effects, and a maximal random effects structure that was qualified by the experimental design (Barr, Levy, Scheepers, & Tily, 2013). At this point, the random structure included by-subject and by-item intercepts and slopes. We defined the random effects at the item-level as the variance that was introduced by the sampling of landmark triples for each JRD trial. All JRD trials that involved the same three landmarks (e.g., local landmarks A, B, and C in city 1) were defined as an item, resulting in 16 items in total. Next, we simplified this maximal random effects structure until the model converged by first successively excluding random slopes and then random intercepts. The first model that converged included by-subject intercepts and slopes and by-item intercepts. Note that the model accounts for correlations across data points that result from differences in participants' overall performance (e.g., generally better memory for different participants) and from changes in performance across landmark conditions.

The fixed effects model structure followed a confirmatory hypothesis-driven approach with two main effects (landmark type, spatial tapping), one covariate (WM capacity), and any interactions between these three factors. We also included the trial number as a fixed effect in order to account for the variance that is related to a general practice effect. The full regression model used effects coding with contrasts set to -0.5 and +0.5 for each categorical predictor and with the continuous variable centered (not scaled) at the mean value for the WM span (M=0.655). The lmer formula of the full model with all fixed and random factors was thus:

$$
\begin{aligned}
&JRD\ error\ \sim\ landmark\ type\ *\ spatial\ tapping\ group\ *\ WMspan\ + \\
&\quad trial\ number\ +\ (1\mid triple)\ +\ (1 + landmark\ type \mid participant)
\end{aligned}
$$

Levene's test revealed that the residual variance was not homogeneous across experimental conditions (F= 12.28, p< .001). A log transformation resolved this violation of the homogeneity assumption according to a subsequent Levene's test (F= 1.018, p= .417). Because both models demonstrated the same pattern of results, we report only the non-transformed data below for readability. For the log transformed results, see Figure A1 in the Appendix. Regression plots were created using the R package "sjPlot" (version 2.6.2; Lüdecke, 2018).

Results

On average, our 51 participants required 296 seconds to move from the starting point to the destination of each navigation trial. Participants in the tapping group (M=311 s, SD=33.7 s) required more time to reach the destination than participants in the group without tapping (M=281.18 s, SD=17.43 s), $t(49)$= 3.96, p< .001, d= 1.11. On average, participants also used the navigation aid for 18 seconds (or 6%) of the time they spent on the navigation task. There was no significant difference in the absolute duration of navigational aid use between the tapping group (M=19.62 s, SD=10.28 s) and the group without tapping (M=16.43 s, SD=6.02 s; $t(49)$= 1.36, p= .180). Similarly, when the duration of navigational aid use was normalized with respect to trial duration, there was no significant difference between the tapping group (M=6.20%, SD=2.71%) and the group without tapping (M=5.85%, SD=1.95%; $t(49)$= 0.53, p= .597). We also did not find a significant difference in WM span between the tapping group (M=0.688, SD=0.177) and the group without tapping (M=0.642, SD=0.148; $t(49)$= 0.98, p= .332).

For the SSQ, we found that the total scores increased significantly from pre-task (M=17.97, SD=17.12) to post-task (M=29.7, SD=30.9) measurements, $t(50)$= -3.27, p= .007, d= -0.46. This increase in total score was qualified by significant increases in nausea $t(50)$= -2.94, p= .020, d= -0.41, and disorientation, $t(50)$= -4.27, p< .001, d= -0.6. There was no increase in oculomotor symptoms, $t(50)$= -1.35, p= .185. Furthermore, the increase in total SSQ score was similar for the tapping group (M=8.53, SD=19.92) and the group without tapping (M=14.82, SD=30.19; $t(49)$= 0.87, p= .738).

The SSSQ data indicated a significant effect of the tapping task on participants' affective states. Participants in the tapping group showed a larger increase in distress ratings (*M*=0.9, *SD*=0.77) than participants in the group without tapping (*M*=0.31, *SD*=0.77; $t(49)$= 2.75, p= .025, d= 0.77), indicating an increase in cognitive load. In contrast, tapping did not affect engagement significantly, with similar increases from pre- to post-task measurements in the tapping group (*M*=+0.21, *SD*=0.54) and the group without tapping (*M*=+0.19, *SD*=0.51; $t(49)$= 0.86 , $p>$ .999). Similarly, the tapping task had no significant effect on worry ratings $t(49)$= -0.94, $p>$ .999, with the tapping group (*M*=-0.53, *SD*=0.62) showing similar decreases in worry ratings to the group without tapping (*M*=-0.68, *SD*=0.51). Figure 4 shows the mean ratings of both experimental groups for each subscale before and after the task.

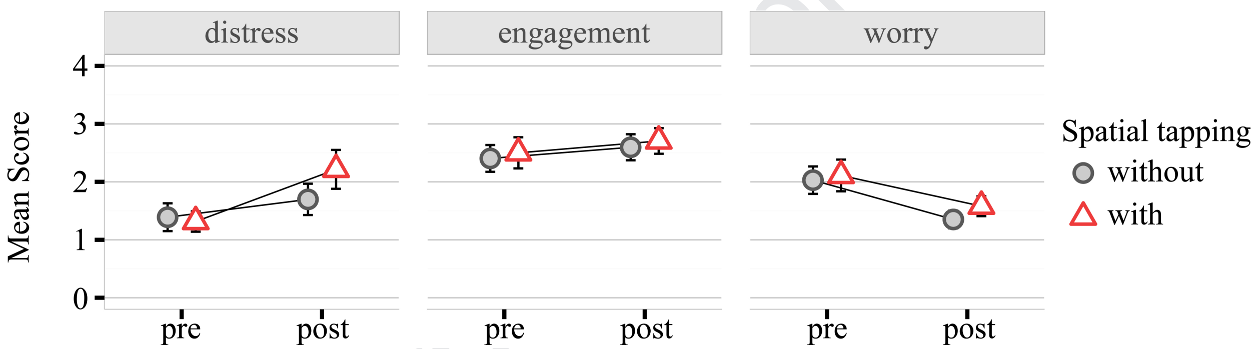


Figure 4. Mean self-reported distress, engagement, and worry for both groups (with / without tapping). Participants' self-reports were taken before and after the experimental procedure. Increases in distress were significantly higher for the tapping group than for the without tapping group.

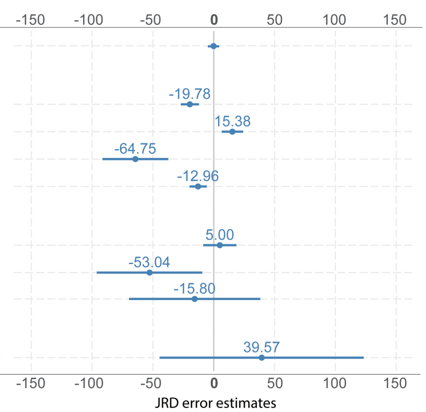
For the 25 participants in the tapping group, the correct tapping rate decreased significantly between baseline measurements (*M*=3.72, *SD*=1.21) and navigation trials (*M*=2.06, *SD*=0.65; $t(24)$= -8.41, $p<$ .001, d= -1.68), suggesting that navigation and tapping required the same set of cognitive resources. However, the correct tapping rate decreased similarly from baseline for local (*M*=-1.71, *SD*=0.97) and global (*M*=-1.62, *SD*=1.06) landmark configurations, $t(24)$= 0.92, p= .730, suggesting that local and global landmark learning relied to similar extents on spatial WM resources (Rudkin, Pearson, & Logie, 2007).

For the EDA data, participants in the tapping group demonstrated a similar increase of SCL from baseline (M=3.01, SD=1.87) than participants in the without tapping group (M=2.01, SD=1.48; $t(46)$= 2.06, p= .09). Furthermore, there was no difference in nSCR/min between the tapping group (M=-0.09, SD=0.24) and the without tapping group (M=-0.12, SD=0.22; $t(46)$= -0.37, p> .999).

JRD Results

Overall, the 51 participants produced 1224 JRDs. The mean angular error was 55.67° (SD=47.77°), and the median angular error was 38.5°. The interquartile range ran from 17.79° to 85.62° in angular error. For a complete table of statistics from the JRD analyses, see Figure 5.

	β	Std. Error	df	t value	p	95% CIs
Intercept	56.01	2.35	35.45	23.80	< 0.0001	(51.39 , 60.62)
Main Effects						
LM (global) ***	-19.78	3.81	26.04	-5.18	< 0.0001	(-27.25 , -12.30)
TAP (with) **	15.38	4.50	47.35	3.42	0.0013	(6.56 , 24.20)
WM span (0.5) ***	-64.75	13.88	47.45	-4.66	< 0.0001	(-91.97 , -37.54)
trial_number (2) ***	-12.96	3.63	46.28	-3.57	0.0009	(-20.09 , -5.84)
Two-Way Interactions						
LM x TAP	5.00	7.005	46.16	0.71	0.4789	(-8.73 , 18.73)
LM x WM span *	-53.04	22.24	46.02	-2.38	0.0212	(-96.64 , -9.44)
TAP x WM span	-15.80	27.67	46.96	-0.57	0.5707	(-70.05 , 38.43)
Three-Way Interaction						
LM x TAP x WM span	39.57	43.00	45.37	0.92	0.3623	(-44.71 , 123.86)



LM = Landmark Type; TAP = Spatial Tapping; WM = Working Memory, CIs = Confidence Intervals

*** $p < .001$; ** $p < .01$; * $p < .05$

Figure 5. A list of the fixed effects regression coefficients using orthogonal contrasts. The intercept is the grand mean, and other coefficients are the estimated differences between a group mean and the grand mean. Confidence intervals were computed using the Wald test. There were significant main effects found for landmark type, tapping, WM span, and trial number. Interestingly, the two-way interaction indicated that the effects of landmark type and WM span varied with respect to each other.

The linear mixed effects model revealed significant main effects for landmark type, tapping group, WM span, and trial number, as well as a significant interaction between landmark type and WM span. Specifically, participants in the tapping group had a significantly higher JRD error than participants in the without tapping group. The tapping group effect did not interact with landmark type or WM span. Participants' JRDs also improved, on average, by 12.96 degrees from the first trial to the second trial, suggesting a general practice effect. In addition, the significant main effects of WM span and landmark type are qualified by a two-way interaction. In order to understand the manner in which WM span moderated the effect of landmark type on JRD error, we modeled the marginal effects of WM span on JRD errors separately for local and global landmark configurations (averaged over levels of the other factors). Figure 6 visualizes the relationship between JRD error and WM span with separate regression lines for local and global landmarks.

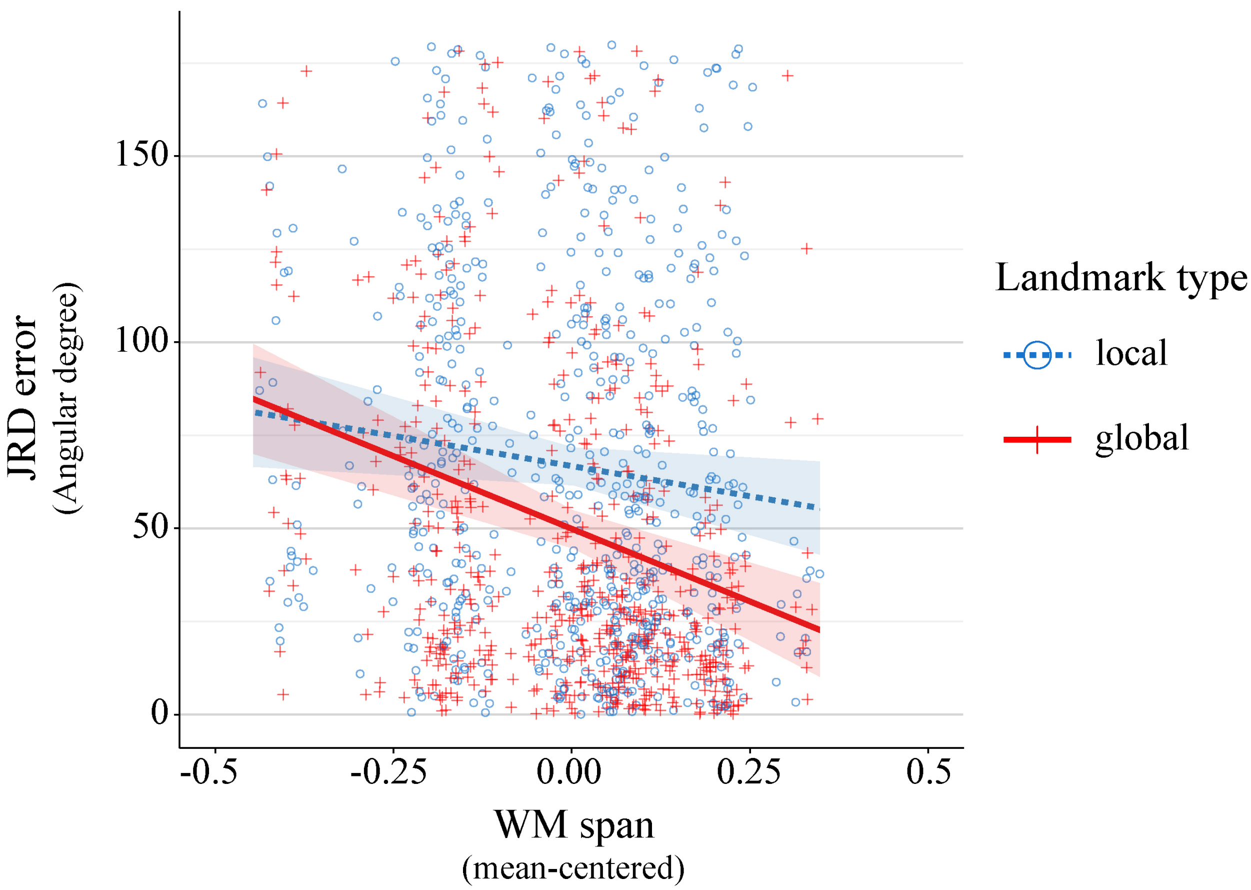


Figure 6. Predicted estimates of JRD error as a result of WM span and landmark condition. The model predicted that with increasing WM span, the error would decrease more for global landmark representations than for local landmark representations.

This plot suggests that participants with higher WM spans mentally integrate global landmark configurations more accurately into a survey representation than local landmark configurations during navigation. After testing each of these two regression lines, we demonstrated that JRD errors for local landmark configurations did not significantly decrease with higher WM span, β= -38.7, SE$_\beta$= 17, $t(48)$= -2.15, p= .073, 95% CI [-74, -2.5]. However, WM span strongly affected JRD errors involving global landmark configurations, β= -91.1 , SE$_\beta$= 18, $t(48)$= -5.1, $p<$ .001, 95% CI [-127, -55.3]. Finally, contrary to our expectations, there was no significant three-way interaction. This means that high WM span did not affect the accuracy of survey knowledge acquisition for local and global landmark configurations differently for the with or without spatial concurrent task groups.

Discussion

We studied the role of spatial WM on survey knowledge acquisition based on local and global landmark configurations during navigation in virtual cities. Our findings specify this role in at least two ways. First, the spatial-sequential concurrent task limited both navigation performance and survey knowledge acquisition, suggesting that the same WM resources are employed for these two tasks. Second, individual differences in WM span measured before navigation interacted with landmark type such that participants with a higher WM span recalled globally visible landmark configurations that were perceived simultaneously across the traversed environment more accurately than local landmark configurations that were viewed sequentially only when traveling nearby.

Our findings are consistent with prior research that found superior spatial memory for object-to-object relations when locations were presented simultaneously (rather than sequentially) for small (R. J. Allen et al., 2006; Blalock & Clegg, 2010; Lecerf & De Ribaupierre, 2005) and room-sized spaces (Lupo et al., 2018; Meilinger et al., 2016). The present study extends these prior findings to locations learned during navigation through large environments, such as cities, in VR. Our results connect findings related to spatial WM across spatial scales and indicate the potential of VR for research that seeks to understand the mechanisms underlying navigation and survey knowledge acquisition. In comparison to our previous investigation (Credé et al., 2019), the present data demonstrate that the advantage of memorizing global landmarks in a common survey knowledge representation only occurs when the landmarks are located along the route rather than located at a far distance. Notably, the effect of landmark type obtained in the present study was qualified by an interaction with WM span. Participants with higher WM spans were able to exploit the simultaneous visibility of global landmarks to acquire more accurate survey knowledge. These results confirm findings from previous research that have shown individual differences in the ability to acquire accurate metric knowledge about space (Ishikawa & Montello, 2006; Schinazi, Nardi, Newcombe, Shipley, & Epstein, 2013) and the importance of WM for survey knowledge acquisition (G. L. Allen et al., 1996; Hegarty et al., 2006). However, our findings do not support a relationship between WM span and individuals' abilities to resist the negative effects of concurrent task load (Ilkowska & Engle, 2010). The positive relationship between WM span and JRD performance was similar in the tapping and no tapping groups.

We also expected the tapping task to affect survey knowledge acquisition for different landmark configurations to the extent that their encoding relied on spatial WM, but our results did not reveal an interaction between tapping group and landmark type. Hence, it remains unclear whether the interference caused by the tapping task in this study was domain-general or specific to a particular WM subsystem. According to a domain-general interpretation of our results, the tapping task may have impaired several cognitive functions and redirected attentional resources away from the knowledge acquisition task (Barrouillet, Portrat, & Camos, 2011; Kane & Engle, 2003). This explanation is consistent with several studies that demonstrated interference across domains (e.g., Garden, Cornoldi, & Logie, 2002; Vergauwe, Barrouillet, & Camos, 2010). According to a domain-specific interpretation of the present results, survey knowledge acquisition for local and global landmark configurations may have relied on spatial WM in a similar manner despite differences in the visibility of the two types of landmarks. This interpretation is inconsistent with previous studies that have suggested that simultaneously visible objects require less processing in spatial WM than sequentially visible objects (e.g., Lecerf & De Ribaupierre, 2005).

Another implication of this domain-specific interpretation is that WM span affects the encoding of local landmark configurations more than the encoding of global landmark configurations. However, our results demonstrate the opposite effect. Participants' performance in global landmark learning benefited comparatively more from high WM spans. These results may be attributable to a floor effect for our measure of survey knowledge because we found poorer performance on the JRD tasks than most previous studies (e.g., Huffman & Ekstrom, 2018; Schinazi et al., 2013; Zhang, Zherdeva, & Ekstrom, 2014). One possible explanation for this floor effect is that participants in the present study were only exposed to each environment for one navigation trial. Indeed, previous research has shown that survey knowledge assessed using JRDs improves significantly with increasing exposure to the environment (Huffman & Ekstrom, 2018; Zhang et al., 2014). However, some studies have found that participants do not significantly gain accuracy in survey knowledge over multiple trials along the same route (e.g., Schinazi et al., 2013). Another possible explanation for our floor effect is too little training on the JRD task itself. For example, our results revealed a significant effect of trial number, although the two navigation trials employed different (counterbalanced) sets of landmarks. Future studies may need to include additional navigation trials to assess potential learning effects as well as extensive training on the JRD task (with feedback) to reduce general task difficulty. To disentangle domain-general and domain-specific interpretations of such results, future research could also include an experimental group that performs a domain-specific, but non-spatial, task (e.g., generating random digits). One important consideration for this approach would be to match the various domain-specific tasks in terms of overall difficulty.

Our findings are also consistent with prior research that demonstrated the detrimental effects of spatial interference tasks on navigators' abilities to encode spatial relations among landmarks during navigation in VR (Gras et al., 2013; Labate et al., 2014;

Wen et al., 2013). This interference can be considered as an indication that both a tapping task and survey knowledge acquisition are drawing upon the same set of cognitive resources (Lindberg & Gärling, 1981). Compared to the group without the tapping task, the group with the tapping task demonstrated a trend of higher SCL during navigation and significantly larger increases in self-reported distress from the beginning to the end of the experiment. Both of these effects have been attributed to a large investment of cognitive resources via task demands in related work (Engström et al., 2005; Matthews et al., 2002). This tapping task can thus also be used to induce cognitive load for experimental purposes. However, participants may also experience a negative psychophysiological stress response, which might not be a desired outcome. Future research could further disentangle the effects of concurrent (tapping) tasks on cognitive load and its effect on human emotions such as stress.

Similar to these tapping tasks, most interactions with current smart assistive devices (e.g., SatNav systems) involve tapping on a display of some sort. Thus, our results have direct practical implications for the design of future digital navigation assistance systems that would support survey knowledge acquisition even while a navigator is multi-tasking. Indeed, people often navigate while performing several other tasks (e.g., talking to a travel companion, using the phone) and/or thinking about unrelated events (e.g., an upcoming birthday, an emotional conflict from earlier in the day). Such tasks may redirect attentional resources away from navigation and spatial learning in a domain-general manner and eventually cause disorientation. Our results suggest that it is important to emphasize global landmarks dynamically on digital navigation systems to prevent disorientation and support spatial knowledge acquisition. This approach should be especially beneficial for navigators with high WM spans.

References

Allen, G. L., Kirasic, K. C., Dobson, S. H., Long, R. G., & Beck, S. (1996). Predicting environmental learning from spatial abilities: An indirect route. *Intelligence*, *22*(3), 327–355.

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General*, *135*(2), 298–313.

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417–423.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of memory and language*, *68*(3), 255–278.

Barrouillet, P., Portrat, S., & Camos, V. (2011). On the law relating processing to storage in working memory. *Psychological Review*, *118*(2), 175–192.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. doi: 10.18637/jss.v067.i01

Benedek, M., & Kaernbach, C. (2010). A continuous measure of phasic electrodermal activity. *Journal of neuroscience methods*, *190*(1), 80–91.

Blalock, L. D., & Clegg, B. A. (2010). Encoding and representation of simultaneous and sequential arrays in visuospatial working memory. *Quarterly Journal of Experimental Psychology*, *63*(5), 856–862.

Boucsein, W. (2012). *Electrodermal activity.* Springer Science & Business Media.

Castelli, L., Latini Corazzini, L., & Geminiani, G. C. (2008). Spatial navigation in large-scale virtual environments: Gender differences in survey tasks. *Computers in Human Behavior*, *24*(4), 1643–1667.

Coluccia, E., Bosco, A., & Brandimonte, M. A. (2007). The role of visuo-spatial working memory in map learning: New findings from a map drawing paradigm. *Psychological* *research*, *71*(3), 359–372.

Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic bulletin & review*, *12*(5), 769–786.

Couclelis, H., Golledge, R. G., Gale, N., & Tobler, W. (1987). Exploring the anchor-point hypothesis of spatial cognition. *Journal of Environmental Psychology*, *7*(2), 99–122.

Credé, S., Thrash, T., Hölscher, C., & Fabrikant, S. I. (2019). The acquisition of survey knowledge for local and global landmark configurations under time pressure. *Spatial Cognition & Computation*, 1–30.

Darling, S., Della Sala, S., & Logie, R. H. (2007). Behavioural evidence for separating components within visuo-spatial working memory. *Cognitive processing*, *8*(3), 175–181.

Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation research part F: traffic psychology and behaviour*, *8*(2), 97–120.

Figner, B., & Murphy, R. O. (2011). Using skin conductance in judgment and decision making research. *A handbook of process tracing methods for decision research*, 163–184.

Fisk, J. E., & Sharp, C. A. (2003). The role of the executive system in visuo-spatial memory functioning. *Brain and Cognition*, *52*(3), 364–381.

Freeman, J., Lessiter, J., Pugh, K., & Keogh, E. (2005). When presence and emotion are related, and when they are not. In *Proceedings of the 8th annual international workshop on presence (presence 2005)* (pp. 213–219).

Garden, S., Cornoldi, C., & Logie, R. H. (2002). Visuo-spatial working memory in navigation. *Applied Cognitive Psychology*, *16*(1), 35–50.

Golledge, R. G. (Ed.). (1999). *Wayfinding behavior: Cognitive mapping and other spatial processes.* JHU press.

Gras, D., Gyselinck, V., Perrussel, M., Orriols, E., & Piolino, P. (2013). The role of working memory components and visuospatial abilities in route learning within a virtual environment. *Journal of Cognitive Psychology*, *25*(1), 38–50.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence*, *34*(2), 151–176.

Helton, W. S. (2004). Validation of a Short Stress State Questionnaire. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *48*(11), 1238–1242.

Huffman, D. J., & Ekstrom, A. D. (2018). Which way is the bookstore? a closer look at the judgments of relative directions task. *Spatial Cognition & Computation*, 1–37.

Ilkowska, M., & Engle, R. W. (2010). Trait and state differences in working memory capacity. In *Handbook of individual differences in cognition* (pp. 295–320). Springer.

Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive psychology*, *52*(2), 93–129.

Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, memory, and cognition*, *26*(3), 683.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to stroop interference. *Journal of experimental psychology: General*, *132*(1), 47.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*(2), 189.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The* *international journal of aviation psychology*, *3*(3), 203–220.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. doi: 10.18637/jss.v082.i13

Labate, E., Pazzaglia, F., & Hegarty, M. (2014). What working memory subcomponents are needed in the acquisition of survey knowledge? evidence from direction estimation and shortcut tasks. *Journal of Environmental Psychology*, *37*, 73–79.

Lecerf, T., & De Ribaupierre, A. (2005). Recognition in a visuospatial memory task: The effect of presentation. *European Journal of Cognitive Psychology*, *17*(1), 47–75.

Lenth, R. (2019). emmeans: Estimated marginal means, aka least-squares means [Computer software manual]. (R package version 1.3.2)

Li, H., Corey, R. R., Giudice, U., & Giudice, N. A. (2016). Assessment of visualization interfaces for assisting the development of multi-level cognitive maps. In *International conference on augmented cognition* (pp. 308–321).

Li, R., Korda, A., Radtke, M., & Schwering, A. (2014). Visualising distant off-screen landmarks on mobile devices to support spatial orientation. *Journal of Location Based Services*, *8*(3), 166–178.

Lindberg, E., & Gärling, T. (1981). Acquisition of locational information about reference points during blindfolded and sighted locomotion: Effects of a concurrent task and locomotion paths. *Scandinavian Journal of Psychology*, *22*(1), 101–108.

Logie, R. H., & Marchetti, C. (1991). Visuo-spatial working memory: Visual, spatial or central executive? In *Advances in psychology* (Vol. 80, pp. 105–115). Elsevier.

Lüdecke, D. (2018). sjplot: Data visualization for statistics in social science [Computer software manual]. (R package version 2.6.2) doi: 10.5281/zenodo.1308157

Lupo, M., Ferlazzo, F., Aloise, F., Di Nocera, F., Tedesco, A., Cardillo, C., & Leggio, M. (2018). New protocol for dissociating visuospatial working memory ability in reaching space and in navigational space. *Behavior Research Methods*, *50*(4), 1602–1613. doi:

10.3758/s13428-018-1047-2

Mackworth, J. F. (1962). The effect of display time upon the recall of digits. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *16*(1), 48.

Matthews, G., Campbell, S. E., Falconer, S., Joyner, L. A., Huggins, J., Gilliland, K., ... Warm, J. S. (2002). Fundamental dimensions of subjective state in performance settings: Task engagement, distress, and worry. *Emotion*, *2*(4), 315.

Matthews, G., Joyner, L., Gilliland, K., Campbell, S., Falconer, S., & Huggins, J. (1999). Validation of a comprehensive stress state questionnaire: Towards a state big three. *Personality psychology in Europe*, *7*, 335–350.

Meilinger, T., Strickrodt, M., & Bülthoff, H. H. (2016). Qualitative differences in memory for vista and environmental spaces are caused by opaque borders, not movement or successive presentation. *Cognition*, *155*, 77–95. doi: 10.1016/j.cognition.2016.06.003

Montello, D. R. (1993). Scale and multiple psychologies of space. In *European conference on spatial information theory* (pp. 312–321).

Münzer, S., Zimmer, H. D., & Baus, J. (2012). Navigation assistance: A trade-off between wayfinding support and configural learning support. *Journal of Experimental Psychology: Applied*, *18*(1), 18–37. doi: 10.1037/a0026553

Navarro, D. (2015). Learning statistics with r: A tutorial for psychology students and other beginners. (version 0.5) [Computer software manual]. Adelaide, Australia. (R package version 0.5)

Oberauer, K., & Göthe, K. (2006). Dual-task effects in working memory: Interference between two processing tasks, between two memory demands, and between storage and processing. *European Journal of Cognitive Psychology*, *18*(4), 493–519.

Oberauer, K., Lange, E., & Engle, R. W. (2004). Working memory capacity and resistance to interference. *Journal of Memory and Language*, *51*(1), 80–96.

O'Keefe, J. (1991). An allocentric spatial model for the hippocampal cognitive map. *Hippocampus*, *1*(3), 230–235.

R Core Team. (2018). R: A language and environment for statistical computing [Computer software manual]. Vienna, Austria.

Rudkin, S. J., Pearson, D. G., & Logie, R. H. (2007). Executive processes in visual and spatial working memory tasks. *The Quarterly Journal of Experimental Psychology*, *60*(1), 79–100.

Ruotolo, F., Ruggiero, G., Vinciguerra, M., & Iachini, T. (2012). Sequential vs simultaneous encoding of spatial information: a comparison between the blind and the sighted. *Acta psychologica*, *139*(2), 382–389.

Sadalla, E. K., Burroughs, W. J., & Staplin, L. J. (1980). Reference points in spatial cognition. *Journal of experimental psychology: human learning and memory*, *6*(5), 516–528.

Schinazi, V. R., Nardi, D., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2013). Hippocampal size predicts rapid learning of a cognitive map in humans. *Hippocampus*, *23*(6), 515–528.

Schwering, A., Krukar, J., Li, R., Anacta, V. J., & Fuest, S. (2017). Wayfinding through orientation. *Spatial Cognition & Computation*, *17*(4), 273–303.

Sholl, M. J., & Fraone, S. K. (2004). Visuospatial working memory for different scales of space. In G. L. Allen (Ed.), *Human spatial memory: Remembering where.* (pp. 67–100). Lawrence Erlbaum Associates.

Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. In H. W. Reese (Ed.), (Vol. 10, pp. 9–55). JAI.

Steck, S. D., & Mallot, H. A. (2000). The role of global and local landmarks in virtual environment navigation. *Presence: Teleoperators & Virtual Environments*, *9*(1), 69–83.

Ulrich, R. S. (1981). Natural versus urban scenes: Some psychophysiological effects. *Environment and behavior*, *13*(5), 523–556.

Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological science*, *21*(3), 384–390.

Wen, W., Ishikawa, T., & Sato, T. (2013). Individual differences in the encoding processes of egocentric and allocentric survey knowledge. *Cognitive science*, *37*(1), 176–192.

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in cognitive sciences*, *14*(3), 138–146.

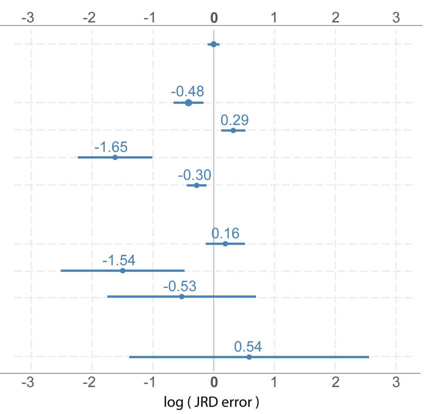
Yamamoto, N., & Shelton, A. L. (2009). Sequential versus simultaneous viewing of an environment: Effects of focal attention to individual object locations on visual spatial learning. *Visual Cognition*, *17*(4), 457–483.

Zhang, H., Zherdeva, K., & Ekstrom, A. D. (2014). Different "routes" to a cognitive map: dissociable forms of spatial knowledge derived from route and cartographic map learning. *Memory & cognition*, *42*(7), 1106–1117.

Appendix

Table of coefficients on logarithmic scale

	β	Std. Error	df	t value	p	95% CIs
Intercept	3.53	0.06	30.1	63.78	< .0001	(3.42 , 3.64)
Main Effects						
LM (global) ***	-0.48	0.10	21.58	5.07	< .0001	(-0.67 , -0.29)
TAP (with) **	0.29	0.10	47.59	2.95	.0049	(0.10 , 0.49)
WM span (high) ***	-1.65	0.31	47.81	-5.34	< .0001	(-2.25 , -1.04)
trial_number (2) ***	-0.30	0.08	46.74	3.57	.0005	(-0.46 , -0.14)
Two-Way Interactions						
LM x TAP	0.16	0.16	46.16	0.71	.3238	(-0.16 , 0.48)
LM x WM span **	-1.54	0.51	46.02	2.38	.0044	(-2.54 , -0.53)
TAP x WM span	-0.53	0.61	46.96	0.57	.3884	(-1.73 , 0.67)
Three-Way Interaction						
LM x TAP x WM span	0.54	0.99	45.43	0.54	.5862	(-1.40 , 2.49)



LM = Landmark Type; TAP = Spatial Tapping; WM = Working Memory, CIs = Confidence Intervals
*** p < .001; ** p < .01; * p < .05

Figure A1. A list of the fixed effects regression coefficients based on the log-transformed data. The intercept is the grand mean, and other coefficients are estimated differences between a group mean and the grand mean. Confidence intervals were computed using the Wald test. As in the untransformed data, there were significant main effects of landmark type, tapping group, WM span, and trial number.

Highlights for
"The advantage of globally visible landmarks for spatial learning"

Overall, memory is more accurate for global than for local landmark configurations (82)

Individual WM capacity improves global more than local landmark memory (70)

Spatial learning of local and global landmarks declines equally under high task load (84)

High task load increases participants' self-reported and physiological distress (79)